Managing Landscape Disturbances to Increase Watershed Infiltration

J. V. Bonta

Abstract. *Agricultural land undergoing conversion to conventional urban development can drastically increase runoff and degrade water quality. A study of landscape management for improving watershed infiltration was conducted using readily available runoff data from experimental watersheds. This article focuses on watershed infiltration changes that can be expected from soil surface and soil profile changes and provides support for low-impact development (LID) options. The investigation uses data from a controlled study of the effects of low percentage imperviousness (~0.6%) and connected and disconnected rooftop-channel configurations (189 m^2 roof structures), as well as agricultural land management types including pastures where cows trample the soil surface and watersheds in hay production (meadow, no land disturbance). Additionally, a published study on the effects of soil profile destruction and equipment compaction in a mine-reclamation study is presented as a comparison and represents disturbances similar to those in urbanization. Impacts are determined through curve number (CN; ordered asymptotic procedure) and peak flow rate changes using two ~3 ha experimental agricultural watersheds located at the North Appalachian Experimental Watershed at Coshocton, Ohio. No statistical effects on CN and peak flow rates were found due to either percentage imperviousness or spatial location at a low level of percentage imperviousness. CN and peak flows for pasture were significantly larger compared with meadow. One watershed was pastured for 29 years followed by a 3.7-year period of meadow, resulting in a statistically significant recovery of watershed infiltration (CN decreased 17.4 CN units from 77.0 to 59.6). Peak flow response to rainfall for the pastured watershed also significantly decreased during hay. These results suggest that watershed infiltration recovers and peak runoff decreases in a short period of time when transitioning from soil surfaces disturbed by pasture-like disturbances to undisturbed grass. This benefit is partly attributed to minimal disturbance of the soil profile and structure that maintains macropore connectivity, and to freeze-thaw cycles affecting the soil. However, CN can increase and remain high if the soil profile is disturbed and is subjected to compaction, as found in a study of the hydrological effects of drastically disturbing the landscape during mine reclamation. In that study, the entire soil profile was disturbed, causing a CN increase to approximately 89 even after reclaiming the landscape by planting grass, regardless of the composition of soil derived from the original geological profile. No recovery of CN was apparent during a three-year post-reclamation (revegetated) monitoring period. The results quantify the conservation principles advocated in LID and green infrastructure. The sum-of-squares-reduction statistical test works well to identify differences in CN and k due to watershed treatments, but the results can be sensitive to the distribution and clustering of rainfall and CN values. Existing experimental watershed data can provide guidance on managing soil surfaces and profiles to minimize CN under conversion of agricultural land to urban development.*

Keywords. *Curve number, Experimental watershed, Grazing, Green infrastructure, Imperviousness, Land management, Low-impact development, Mine reclamation, Pasture, Urbanization.*

Agricultural, urban, and mining and reclamation activities can disturb the soil surface and profile of a landscape to varying degrees and alter the infiltration and runoff response of a watershed to the weather. Soil can be resilient and infiltration can recover from minor surface disturbances, but the landscape may not recover or recover slowly if drastically disturbed. Box (1978) considers an area drastically disturbed "if the native vegetation and animal communities have been removed and most of the topsoil is lost, altered, or buried. These drastically disturbed sites will not completely heal themselves within the lifetime of man through normal secondary successional process" (p. 2). This definition describes some activities that are found on agricultural areas undergoing conversion to conventional urban development, as well as in mined and reclaimed areas. Drastic disturbances can notably decrease infiltration, increase runoff, and degrade water quality from increased imperviousness, characterized by permanently disturbed naturally high infiltration areas and complete soil profile removal. While drastically disturbed areas will be slow to recover infiltration, there is a threshold for disturbance below which impacts may not be apparent, and impacts of some disturbances may even be reversed. Readily available

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The author is **James V. Bonta, ASABE Member,** Research Hydraulic Engineer, USDA-ARS National Sedimentation Laboratory, P.O. Box 1157, 598 McElroy Drive, Oxford, MS 38655; phone: 662-232-2938; email: jim.bonta@ars.usda.gov.

experimental watershed data have the potential to provide guidance on how the soil can be managed to minimize environmental impacts in streams in urbanizing areas.

Landscape management alternatives that minimize environmental impacts have been suggested by adopting low-impact development (LID) to integrate and decentralize runoff control. Runoff rates and volumes can be reduced to flow magnitudes at or below those draining the undisturbed landscape condition (e.g., Dietz and Clausen, 2008). LID practices include bioretention practices (from small rain gardens to larger installations), swales, rain barrels, permeable pavements, vegetated roofs, and minimizing the connectedness of impervious areas and streams. Green infrastructure (GI) is a newer term that suggests flexibility in managing landscapes and utilizing natural hydrological processes and landscape characteristics to reduce and clean excess runoff, and/or identifying landscape components to avoid. GI supports LID principles by utilizing vegetation and soil, including natural processes such as infiltration, percolation, and evapotranspiration, as well as reuse of runoff.

The need for LID/GI practices results from the runoff and water quality impacts of soil surface and profile disturbances during development of an area. Increased runoff from impervious areas is dependent on many factors, including the extent, location, type, and geometry of the impervious surfaces. Adding impervious surfaces to a landscape increases the hydraulic efficiency of a watershed by generating more overland flow (Johnson and Sayre, 1973; Chang, 2007). Increasing the percentage of imperviousness also decreases the amount of stored soil water (Booth, 2000). Runoff from impervious areas that flows onto pervious soils can also quickly saturate the soil and expand the runoff-producing areas (Leopold, 1991).

Definitions of imperviousness are based on the extent of imperviousness and whether impervious areas are directly connected to the stream channel ("connectedness"). Total impervious area (TIA) as a measure of imperviousness does not account for the location of impervious surfaces, and it excludes permeable surfaces with little soil water storage that have the potential to produce runoff during large rainfall events (Booth and Jackson, 1997). The shape and configuration of these surfaces and their connections to stream channels affect the runoff volume delivered to streams. For example, roads have much potential to generate runoff to adjacent ditches (Jones et al., 2000), but roof runoff directed to an infiltrating area such as a small rain garden will not likely flow directly to a stream unless the water storage capacity is exceeded. An "effective" imperviousness area (EIA) improves the definition of TIA to quantify runoff-producing areas that are connected to swales and stream channels (Booth and Jackson, 1997). Booth and Jackson (1997) found that an EIA of 10% was a threshold that "typically yields demonstrable, and probably irreversible, loss of aquatic-system function" (p. 1084). "Ineffective" impervious surfaces force runoff to more permeable surfaces (Alley and Veenhuis, 1983; Walesh, 1989). There are no simple methods to quantify imperviousness that incorporate spatial location and subsequent changes in soil water storage potential.

An important component of GI and LID is to use the functional water storage capabilities of the soil surface and profile, which is the part of a watershed that influences runoff generation and infiltration. A principle of LID/GI is to leave some areas undisturbed to take advantage of this water storage potential to minimize the connectivity of impervious areas and stream conveyances and to maximize the time for concentration and infiltration opportunities.

Many larger watershed-scale studies have been conducted documenting the runoff-reducing benefits of LID management practices in areas undergoing urban development. A watershed-scale study was conducted to evaluate the effectiveness of LID practices at the Jordan Cove Urban Watershed Project in Waterford, Connecticut. This project compared conventional and LID developments and investigated swales, pervious pavements, and bioretention areas. Among the results from this project, Hood et al. (2007) found that conventional watersheds had more peaked hydrographs and shorter lag times for less extreme events compared with LID development. Dietz and Clausen (2008) found significant reductions in runoff due to LID and drastic increases due to conventional development. Dietz (2007) reviewed a wide range of current practices for LID implementation, including bioretention cells, porous pavements, and green roofs. He concluded that a methodology for giving land owners and developers runoff credits is inconsistent among different LID practices. Quantifying the effectiveness of individual LID practices on a large watershed scale is valuable; however, spatial and temporal precipitation variability, isolation of the effectiveness of individual practices, lack of control of watershed activities, and less than 100% implementation of a planned watershed treatment are problems that can affect data interpretation.

In addition to field studies, modeling is an invaluable tool for estimating the impacts of best management practices (BMPs). However, quantifying the effects of spatial location of elements and BMPs is difficult. Bosley (2008) screened 19 watershed models that had potential to simulate effectiveness of LID practices. Two models were selected for further study, and three models specifically designed for LID modeling were not selected. An important finding of the review by Shuster et al. (2005) was that the USDA Natural Resources Conservation Service (NRCS) curve number (CN) model (Hawkins et al., 2009), which is widely used to estimate runoff volumes, is based on limited field data in urbanizing areas. Excellent literature reviews on urbanization by Shuster et al. (2005) and Jacobson (2011) identify research needs on imperviousness and urban BMPs. Three leading resources that provide the current state of the art for design and incorporation of LID practices can be found at the Center for Watershed Protection (www.cwp.org), the University of New Hampshire Stormwater Center (www.unh.edu/unhsc), and the Low-Impact Development Center (www.lid-stormwater.net).

Many studies of small, individual runoff and water quality control practices in urbanizing areas have been summarized to aid conservation practitioners in selecting appropriate practices (Geosyntec, 2012a, 2012b). However, such studies can be expensive and require a minimum number and wide range of weather events to arrive at conclusions regarding performance, factors over which the researcher has no control (e.g., droughts will require extending a project often funded for only a short duration). Furthermore, control of the monitored watershed area is often difficult, and anthropogenic activities are often unknown, complicating data interpretations. As mentioned above, larger watershed studies can include multiple single-practice areas, further confounding interpretation of the individual practices.

One alternative to expensive field studies is to analyze existing small experimental agricultural watershed runoff data under single management practices that can be considered relevant analogs for landscape management for controlling infiltration and runoff. Many experimental watersheds, such as those operated by the USDA Agricultural Research Service (ARS), have permanent precipitation and stream monitoring infrastructure under which a wide range of landscape conditions have been evaluated. Data from small experimental watersheds provided the original foundation for the CN procedure and are valuable for advancing runoff estimation methods. These data sets can incorporate long periods of monitoring with a wide range of weather experiences. Such studies are especially important for watersheds that generally yield little runoff because larger runoff-producing events occur infrequently. Furthermore, the effectiveness of a single practice can be established, and interpretation is not confounded by uncontrolled watershed activities.

This study utilizes the wealth of watershed data collected at the ARS North Appalachian Experimental Watershed (NAEW) near Coshocton, Ohio (described later). In particular, this study originates with data collected from watersheds in which an urbanization study was established and utilizes historical runoff data from previous land uses on the same watersheds. Additionally, a published watershed study is included, in which drastic landscape changes resulted from mining and reclamation disturbances and compaction by heavy equipment, to add another dimension to the discussion of landscape disturbance effects. The previous land uses on the urbanization watersheds included meadow (hay production) and grazing.

This study investigates the watershed hydrological effects (runoff volumes and peak flows) of soil surface disturbance (grazing), soil profile disturbance (mining and reclamation), no disturbance (meadow for hay production), infiltration recovery potential for grazing and mining disturbances, and percentage and spatial location of low-level imperviousness. Specific objectives are: (1) to quantify the impact of a low level of imperviousness and the spatial location of imperviousness ("connectedness") on watershed curve number and peak flow response on selected experimental watersheds; (2) to quantify the effects of landscape disturbances (grazing, hay production practices, and mining and reclamation) and their recovery potential on watershed curve number and peak flow response; and (3) to present LID implications. This study takes advantage of an urbanization project established in 2004 on two NAEW watersheds, other land uses on the two sites prior to the urbanization project, and results from a study of complete watershed disturbance due to coal mining and reclamation. Curve number results are presented first, followed by a discussion section.

PROCEDURE

URBAN WATERSHED PROJECT

NAEW watersheds WS185 (2.99 ha) and WS192 (3.07 ha) (fig. 1 and table 1) were chosen for study in 2004

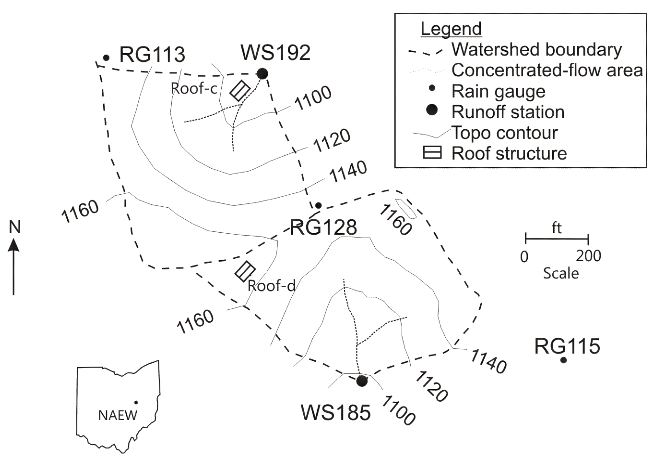


Figure 1. Topographic map and instrumentation for watersheds WS185 and WS192 at the NAEW.

Table 1. Approximate durations of land management and runoff record lengths, and of numbers of runoff events, for WS185 and WS192.

Area (ha)	Latitude and Longitude	Approx. Altitude (m)	Approx. Slope (%)[a]	Land Management: General Land Management Type[b]	Land Management: Approx. Duration (years)	Land Management: Duration of Periods with P and Q Records (years)	First Year of Runoff Record Used	Runoff Events: Total No. of Runoff Events	Runoff Events: No. of Runoff Events Selected
Watershed WS185									
2.99	40° 21′ 31.69595″ N, 81°47′ 45.24634″ W	335.0	12 to 18	Meadow	18.7		1988	74	48
				Roof-d	5.2			76	29
				Total	23.9	7.5		150	77
Watershed WS192									
3.07	40° 21′ 41.29080″ N, 81°47′ 48.92995″ W	330.7	12 to 25	Pasture	29		1975	390	208
				Meadow	3.7			49	31
				Roof-c	5.2			61	22
				Total	37.9	33.8		500	261

[a] From Kelley et al. (1975).
[b] Land management types listed in chronological order.

to investigate the effects of imperviousness and its spatial location (connectedness) on hydrology and water quality under controlled conditions (Bonta, 2006). These two sites were selected because they had historical records of runoff that included periods of prior constant land management. In both sites, a plan for a residential housing development was prepared. Imperviousness, using small roof structures, was to be increased over time after sufficient data to quantify the NRCS curve number were collected at each level of imperviousness. One approach to analyzing the data was to plot a measure of the extent of imperviousness against a response variable (e.g., curve number) and quantify the threshold imperviousness at which an impact was apparent (e.g., Booth and Jackson, 1997).

Each roof consisted of a 189 m^2 (horizontal) low gable roof structure in each watershed (approx. 1.5 m from ground to eaves). In WS185, the roof structure was placed at a distance (~113 m) from the stream channel (identified as roof-d, for "disconnected"). In WS192, the roof structure was placed close (~12 m) to the stream channel near the watershed outlet (identified as roof-c, for "connected") (fig. 1). These two roof configurations were used to quantify the effects of the spatial location of imperviousness. All roof runoff was collected by gutters and pipes to a downspout on the side of the building facing the watershed swale. The roof discharge was allowed to flow downslope over the well protected, grassed land surface. The roof structures occupied 0.63% of the horizontal area for WS185 and 0.62% for WS192. These low levels of imperviousness were not changed due to dry weather (insufficient numbers of runoff events) and the anticipated closure of the NAEW. During the time when the roofs were in place, the rest of the watershed was in a meadow condition maintained by cutting grass or baling hay. This article documents the effects on hydrology (curve number and peak runoff responses) due to the initial low level of imperviousness for all data collected.

Study Area Physical Characteristics

The 424 ha NAEW facility is located in east central Ohio near Coshocton, Ohio (fig. 1) in hilly, unglaciated terrain. It contains nearly flat-lying stratigraphy composed of shale, sandstone, clay, and coal of the Middle Pennsylvanian, Allegheny Formation. Slopes are typically of the order of 12% to 25%. The experimental watersheds concentrate flows in swale areas (no incised channel). Runoff occurs for relatively short durations under heavy rainfall, snowmelt, and wet antecedent soil conditions. The average annual precipitation is 959 mm, and the average annual temperature is 10.4°C. Most peak runoff-producing convective storms occur from June through August.

Fourteen soil types on the two sites were identified in a first-order soil survey conducted by the NRCS in the urbanization sites (fig. 1; Bonta, 2006). Briefly, soils on upper landscape positions were formed in sandstone. Field observations suggest that downward movement of water is not restricted at the interface between parent materials and underlying rock. Consequently, it is assumed that rainfall on this part of the landscape either runs off or moves into the underlying rock. Soils on the lower sideslopes formed in mixed colluvium from sandstone and shale (Bonta, 2006). Additional soils information can be found in Kelley et al. (1975).

Land Management Histories

Beginning in about 1940, the two experimental watersheds used for the urbanization project were subjected to various land management practices for testing their effectiveness to control runoff and water quality. However, only more recent periods were considered in this study, during which land management remained constant up to the time when the imperviousness was installed. For WS185, the watershed was in a meadow practice from about 1988 to 2011 and in a "roof practice" starting about 2006 (table 1). WS192 was used as pasture for approximately 25 to 30 cows beginning in 1975. Starting in about 2003, this watershed was in meadow, and starting in about 2006 the roof was installed. During all land management periods at both sites, the watershed surface was well protected with grass cover. The length of time that the watersheds were in relatively long periods of constant land use ranged from 23.9 years for WS185 to 37.9 years for WS192 (table 1).

In addition to the data collected from the two sites, a published NAEW study on the effects of large landscape-scale disturbances due to mining and reclamation activities on the hydrology of three watersheds in southeast Ohio is included this article (Bonta et al., 1997). The three watersheds were monitored before, during, and after the mining and reclamation disturbances and were situated in three dissimilar parts of the geological column (three different coal seams mined). The three watersheds were C06 (19.8 to 16.6 ha; pre-mine to post-reclamation area), M09 (17.6 to 14.9 ha), and J11 (11.8 to 9.9 ha). All three watersheds experienced near 100% drastic disturbance. C06 had original soils derived mainly from sandstone, M09 had soils derived mainly from shale, and J11 had soil characteristics between the other two sites. The mining and reclamation disturbances were similar to those experienced during some urban development activities. Disturbances included vegetation and topsoil removal, blasting to remove overburden overlying the coal seam, mining the seam, soil compaction consisting of spoil grading and topsoil replacement, and revegetation (Bonta, 2005). While these disturbances are more drastic than those found in urban development, the altered watershed boundaries, the final disturbed soil structure, compacted soil (large bulk density), obliteration of roots, decreased soil carbon, and lack of macropores are characteristics likely found in watersheds and soil profiles disturbed during urban development, all of which are surface soil characteristics that affect stormwater runoff generation.

Data

Runoff data were measured using H flumes (Brackensiek et al., 1979) and drop-box weirs (Bonta and Pierson, 2003). Precipitation was measured at two NAEW gauges adjacent to the watersheds (RG115 and RG113 in fig. 1) using standard weighing-bucket rain gauges. Field runoff and precipitation data were tabulated in breakpoint form with a time resolution of 1 min and depth resolutions of 3 mm (0.01 ft) gauge height for runoff and 0.25 mm (0.01 in.) for precipitation. Records began in about 1940, and all gauges were taken out of operation in November 2011. There were gaps in the records as the watersheds and rain gauges were taken in and out of operation. Consequently, the approximate durations of runoff records for WS185 and WS192 were 7.5 and 33.8 years, respectively, for the land management periods considered (table 1). Precipitation records were composited where there were gaps in the records by duplicating the missing record from another nearby gauge.

Runoff at the mine sites were collected with drop-box weirs (Bonta and Pierson, 2003), and precipitation was measured with weighing-bucket gauges. Data characteristics were similar to those described above. The beginning and ending dates varied by site from 1976 through 1984. The duration of monitoring of final reclamation at the sites was approximately 3.3 years. More detail on the surface water results at the sites can be found in Bonta et al. (1997).

Defining Rainfall-Runoff Events

The program GETPQ96 (Dripchack and Hawkins, 1996) was used to identify event runoff (*Q*) and corresponding causal event precipitation (*P*) for the periods of interest (table 1). The program extracts larger runoff events with peak runoff greater than 0.025 mm h^{-1}. Additionally, because the CN method is a rainfall-runoff model, only rainfall events occurring between the inclusive months of April through October were used. Events were then associated with a period of land management within a watershed.

Computing Curve Numbers

The NRCS curve number method (Hawkins et al., 2009) is used worldwide to compute runoff depths from watersheds. CN is a parameter that quantifies the runoff potential of watersheds and is a function of watershed land use, vegetation, and soil characteristics. The basic equation used to compute runoff depth in the NRCS CN method is:

$$\begin{aligned} Q &= \frac{(P-0.2S)^2}{P+\ 0.8\,S} \qquad P > 0.2S \\ Q &= 0 \qquad\qquad\quad\ P \le 0.2S \end{aligned} \tag{1}$$

where Q is total direct event runoff volume, P is causal event rainfall, and S is potential maximum watershed retention (all variables have length units of millimeters in this article). Equation 1 assumes that the initial watershed abstraction of rainfall (I_a) is a function of S:

$$I_a = 0.2S \tag{2}$$

The variable S, which varies with antecedent soil moisture and other variables, is converted to a CN through the following relationship:

$$\mathrm{CN} = 25400 / (254 + S) \tag{3}$$

Equation 3 constrains the curve number between 0 and 100, with higher curve numbers associated with higher watershed runoff potential (e.g., urbanized areas). Most watershed CNs vary from about 55 to 98.

There are many methods for determining CN; however, the ordered asymptotic method (Hawkins, 1993) is used in this study. Briefly, in this method, the *P-Q* event pairs are separated, *P* and *Q* are ordered separately, and then ordered *P* and *Q* data are merged. The *P* and *Q* data will not likely be naturally paired after ordering and merging; however, the *P* and *Q* data will have the same frequencies of occurrence, an assumption made in engineering application and appropriate for estimating runoff in urban conditions. Ordered data were used instead of “natural” data because preliminary plotting of the data suggested that variability of CN vs. *P* data was considerably reduced using the ordered approach. CN data in the surface mine study also used the ordered approach.

After ordered merging, watershed storage is computed using (Hawkins et al., 2009):

$$S = 5[P + 2Q - (4Q^2 + 5PQ)^{0.5}] \tag{4}$$

and CN is determined using equation 3. CN is then plotted against the corresponding *P*, leading to a trend of decreasing CN as *P* becomes larger. Hawkins (1993) suggested that the data should be fitted to:

$$\mathrm{CN} = \mathrm{CN}_i + (100 - \mathrm{CN}_i)\, e^{-kP} \tag{5}$$

where CN_i is the asymptotic CN, and k is a fitting parameter (mm^{-1}). A larger k results in a CN_i applicable to smaller P, and vice versa. CN_i is the runoff potential of the watershed for large rainfalls and is a function of the limiting interaction of vegetation, land management, and surface and subsurface soil and percolation characteristics for large P. The two parameters were determined using nonlinear regression (implemented as Proc Nlin; SAS, 2012). An enveloping CN_o is typically plotted on an asymptotic graph of CN vs. P, where CN_o is the curve of zero runoff when $P = 0.2S$. CN cannot plot below this line because the CN method assigns $Q = 0$ when $P = 0.2S$ (eq. 1). CN_o is determined by:

$$\mathrm{CN}_o = 25400 / (254 + P/0.2) \tag{6}$$

Because equation 5 is exponential, a measure of a minimum precipitation ($P_{\min}$) above which CN_i is applicable was computed at the point where 99% of the CN_i is reached:

$$P_{\min} = -\ln(0.01)/k \tag{7}$$

Curve Number Comparisons

The CN fittings for periods of constant land use within a watershed (table 1) were compared using the sum-of-squares-reduction test (Hinds and Milliken, 1987; SAS, 2012), a nonlinear analysis of covariance. This procedure assesses the difference in CN_i and k for each land management. Two underlying models comprise this method: one is fitting equation 5 to all data regardless of land management (to determine whether there are overall differences between land management types), and the other uses equation 5 to compute the parameters individually when differences are found in the first test. The former model is termed the “combined model,” and the latter is termed the "full model" because fitting is performed for each land management and there are more parameters. The method fits the two models simultaneously for each land management by using a difference in the parameters.

CN_i for three land management types is formulated as a difference from the main fitting parameter as (CN_{i1} here):

$$CN_iLM_1 = CN_{i1} \text{ for } LM_1 \quad (8)$$

$$CN_iLM_2 = CN_{i1} + CN_id_2 \text{ for } LM_2 \quad (9)$$

$$CN_iLM_3 = CN_{i1} + CN_id_3 \text{ for } LM_3 \quad (10)$$

where LM_i is a classification variable for land management practice *i* (such as roof-c, roof-d, meadow, etc.); CN_id_2 and CN_id_3 are differences from CN_{i1} (e.g., the difference CN_id_2 is between the parameter CN_{i1} in equation 8 for LM_1 and CN_iLM_2 for LM_2 in eq. 9). If zero lies between the upper and lower confidence limits ($\alpha = 0.05$), then there is no difference in a parameter compared with CN_{i1} (e.g., CN_id_2 is not significantly different from zero). If zero lies outside of the confidence interval, then CN_{i1} is different from CN_{i2} for the land management being considered (e.g., $CN_{i2} = CN_{i1} + CN_id_2$). The "fitted parameter estimates" from the method are CN_{i1}, CN_id_2, and CN_id_3 (if two treatments are considered, then CN_iLM_3 and CN_id_3 do not enter the analysis). The "final parameters" are computed from equations 9 and 10. The same procedure is applied to determine whether the *k* parameter is significantly different, and its test is performed simultaneously with CN_i. Tables of results contain the standard error, confidence limits, and fitted and final parameter estimates. The same procedure was followed for comparisons across watersheds, using pooled meadow and roof data.

Where no significant differences were found, a "combined" curve was recomputed by combining the separate land management data sets. The CN differences in similar agricultural management practices were also compared across watersheds using the sum-of-squares-reduction test. The effects of spatial location of the roofs were compared across watersheds using the same sum-of-squares- reduction test. In this case, the pasture data were ignored. A summary table of CN_i for the within and across combinations is presented later in this article.

More importance was placed on whether there were significant differences in CN_i than *k*. This is because there is no theoretical basis for equation 5 to date, and *k* is only a fitting parameter. However, *k* dictates the rate at which CN approaches CN_i and is used to compute $P_{\min}$. CN_i values and combinations are summarized later in this article.

Peak Flow Comparisons

The approach used to determine whether there are differences in peak runoff rates (depth/time) between treatments and watersheds was to combine a peak flow rate with a measure of precipitation intensity that caused the peak. The approach used by Bonta and Rao (1992) in development of a peak flow methodology and Bonta et al. (1997) in evaluating surface mine impacts was followed. Briefly, causal rainfall intensity was computed by first determining the rainfall depth between the beginning of runoff and peak runoff. This depth was divided by the corresponding elapsed time (time to peak) to give average rainfall intensity (depth/time) during the rise to peak runoff rate. It is assumed that the lag time between peak runoff rate and rainfall is negligible because the watersheds are small. The ratio of the peak flow rate to causal rainfall intensity is used as a dimensionless index of the effects of land management on peak flow rate. A smaller ratio implies that the watershed attenuates rainfall intensity more than a larger ratio (i.e., peak flow response per unit of rainfall intensity is smaller). This index incorporates factors that affect peak flow rates, such as soil characteristics, antecedent soil moisture, land management, other watershed characteristics, and rainfall intensity variations.

Statistical comparisons of the ratios between treatments were performed by an analysis of variance test using logarithms of the ratio and the Bonferroni multiple-comparison test (Proc Mixed; SAS, 2012). A similar test was performed for treatment types pooled across water-sheds.

Results and Discussion

There were 150 runoff events identified in the period of runoff record for WS185, with about the same number of events during each land management period (table 1). For WS192, 500 events were identified, with most occurring during the pasture management period. After selecting events that occurred during the rainfall season from April through October, 77 events were available for WS185 and 261 events for WS192. Approximately 62% of the available events were measured in the meadow period at WS185. At WS192, approximately 12% were measured during meadow and 80% during pasture.

Curve Number Comparisons for Disconnected Roof (Roof-d)

The results show that there was no effect of the disconnected roof surface on CN for the small percentage area, and that the watershed behaved as if it were in a meadow land use during the roof-d period for WS185 (table 2). Asymptotic curve number plots for both watersheds during the different watershed conditions all followed the "standard" watershed classification identified by Hawkins (1993) (e.g., fig. 2a). The standard pattern shows CN decreasing to an asymptote as *P* becomes larger (fig. 2a). Figure 2a shows that the best fitted curves for the meadow and roof-d management are nearly the same. The fitted parameter CN estimate for roof-d was 69.7, and that for meadow (difference in CN_i) was 1.8 (fig. 2a and table 2), resulting in final CN_i parameters of 69.7 for roof-d and 71.5 (= 69.7 + 1.8) for meadow. Because the 95% confidence interval includes zero, the meadow CN_i of 71.5 is not significantly different from the roof-d value of 69.7. The simultaneously determined final *k* parameter for meadow (0.0673 mm^{-1}) was also not significantly different from *k* for roof-d (0.0557 mm^{-1}).

Because the curves were not significantly different, the data were combined without reordering to yield an average

Table 2. Fitted parameters and statistical significance from fitting curve numbers to WS185 runoff data (units for k are mm^{-1}).

Watershed Management	Parameter	Final Parameter	P_{min} (mm)	Fitted Parameter Estimate	Standard Error	95% Confidence Limits Lower	95% Confidence Limits Upper	Significant Difference?
Roof-d	CN_i	69.7	36	69.7	1.6	66.6	72.8	no
	k	0.0557		0.0557	0.0064	0.0430	0.0683	no
Meadow	CN_i	71.5	30	1.8	1.8	-1.8	5.3	no
	k	0.0673		0.0117	0.0080	-0.0042	0.0275	no
Combined	CN_i	71.1	31					
	k	0.0638						
Combined (reordered)	CN	71.3	31					
	k	0.0651						

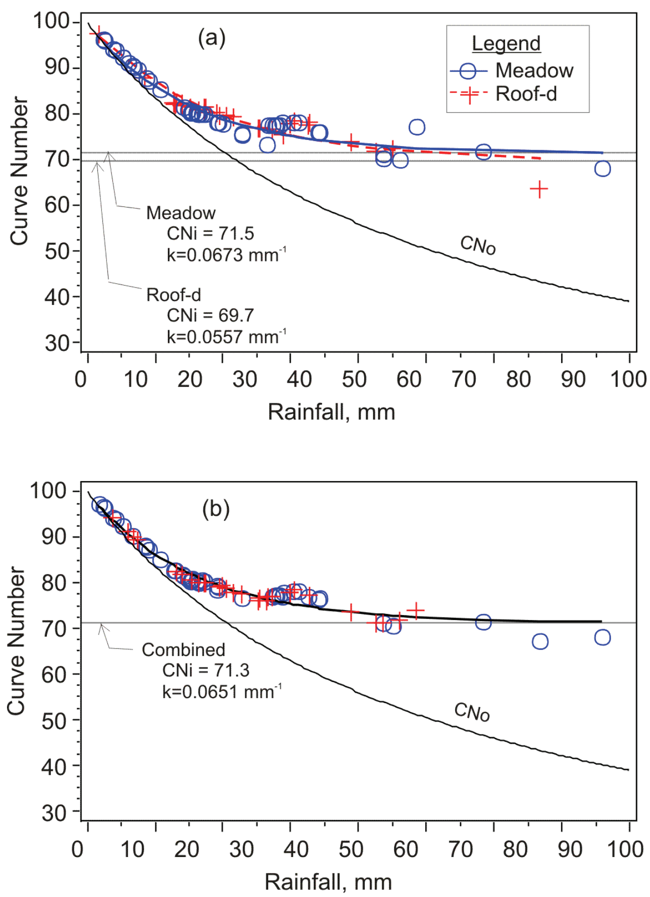


Figure 2. Asymptotic curve fitting for WS185: (a) disconnected roof (roof-d) and meadow land management, and (b) combined roof-d and meadow by reordering data.

CN_i and k of 71.1 and 0.0638 mm^{-1} (table 2). By reordering the data, the corresponding values were nearly identical at 71.3 and 0.0651 mm^{-1} (fig. 2b).

CURVE NUMBER COMPARISONS FOR CONNECTED ROOF (ROOF-C)

The CN_i and asymptotic curves are likely the same, and there is no effect of a roof connected to the stream channel compared with meadow at this small level of imperviousness for WS192 (table 3). Fitted parameter estimates for computing CN_i for WS192 were 59.6 for roof-c, 5.7 for meadow, and 17.3 for pasture (table 3 and fig. 3). These correspond to final parameters for CN_i of 59.6 for roof-c, 65.4 for meadow, and 77.0 for pasture. Final k parameters were 0.0337 mm^{-1} for roof-c, 0.0465 mm^{-1} for meadow, and 0.0772 mm^{-1} for pasture. Each curve is significantly different from the others for both CN_i and k. The CN_i was largest (CN_i = 77.0) for pasture and smallest (CN_i = 59.6) for roof-c. The CN vs. P plot for pasture suggests a slight "violent" response, according to the Hawkins (1993) watershed classification, at $P > 50$ mm. However, more data are necessary to draw a conclusion. While the CN_i are significantly different, the curves for meadow and roof-c are visually close to one another, but both are visually less than pasture (fig. 3a). Their equivalence is supported by considering only a comparison between meadow and roof-c. In this case, zero lies within the confidence limits for the curve fitting, and the final and fitted parameters are the same as for the comparison of all three treatments (table 3). However, the k values are still significantly different. There were only 22 points available for analysis for the roof-c treatment, and more points would be helpful to document differences if differences exist, especially at larger P. The combined roof-c and meadow CN_i and k were 63.2 and 0.0407 mm^{-1}.

Table 3. Fitted parameters and statistical significance from fitting curve numbers to WS192 runoff data (units for k are mm^{-1}).

Watershed Management	Parameter	Final Parameter	P_{min} (mm)	Fitted Parameter Estimate	Standard Error	95% Confidence Limits Lower	95% Confidence Limits Upper	Significant Difference?
Roof-c	CN_i	59.6	59	59.6	1.8	56.0	63.2	yes
	k	0.0337		0.0337	0.0027	0.0284	0.0391	yes
Meadow	CN_i	65.4	43	5.7	2.1	1.6	9.9	yes
	k	0.0465		0.0127	0.0040	0.0049	0.0205	yes
Pasture	CN_i	77.0	26	17.3	1.8	13.7	21.0	yes
	k	0.0772		0.0434	0.0036	0.0364	0.0505	yes
Meadow (compared with roof-c only)	CN_i	65.4	43	5.7	3.2	-0.7	12.2	no
	k	0.0465		0.0127	0.0060	0.0006	0.0248	yes
Meadow and roof-c	CN_i	63.2	49					
	k	0.0407						

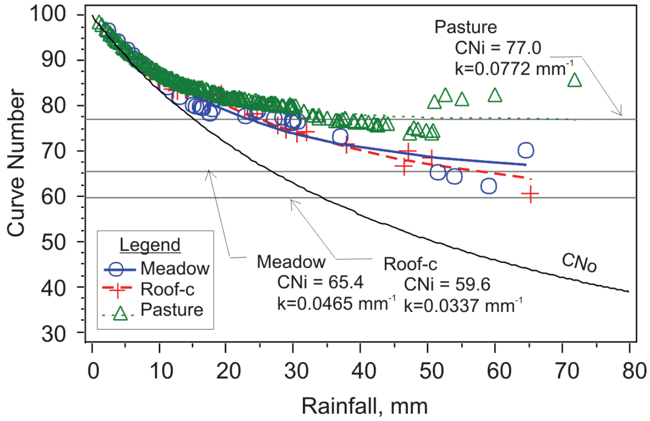


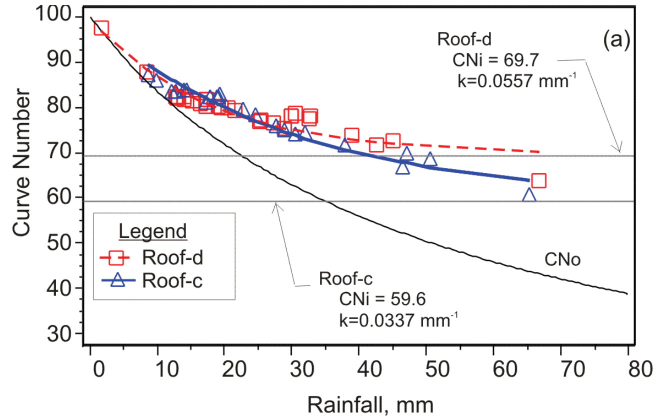
Figure 3. Asymptotic curve fitting for WS192, pasture, roof-c, and meadow land management.

Curve Number Comparisons for Disconnected and Connected Roofs (Roof-d vs. Roof-c)

There are significant differences in CN_i and k between the two roof-location configurations (roof-d vs. roof-c) in the two watersheds (table 4), but there appears to be no practical significance. The final parameter values are the same as calculated before; however, zero is not contained within the confidence interval. CN_i for WS185 with the imperviousness distant from the stream channel is larger (CN_i = 69.7) than CN_i for WS192 in which the imperviousness is close to the stream channel (CN_i = 59.6). Figure 4a shows that event data are clustered for P < 30 mm for WS185, and there is a more uniform distribution of events for larger P for P > 30 mm for WS192. The difference in distributions of the data, especially for larger P, will affect the fitted asymptote. The trend of large P points for both watersheds is similar; however, the fit of the equation to WS185 data is weighted by the smaller P where the curvature of the line is changing rapidly. The combined curve (table 4 and fig. 4b) has a CN_i = 64.6.

Curve Number During Mining and Reclamation

Curve number for the three sites ranged from 71 to 81 for the pre-mined, undisturbed conditions, the soils of which ranged from predominantly sandstone to shale derived soils (Bonta et al., 1997). However, regardless of the starting parent materials in the undisturbed watersheds, the reclaimed CNs were in the narrow range from 87 to 91 (average = 89). This suggests that after the complete destruction of the soil profile, CN will converge to a known constant value, regardless of the geological characteristics from which soils are derived. CN did not recover in the approximately three-year post-reclamation period.



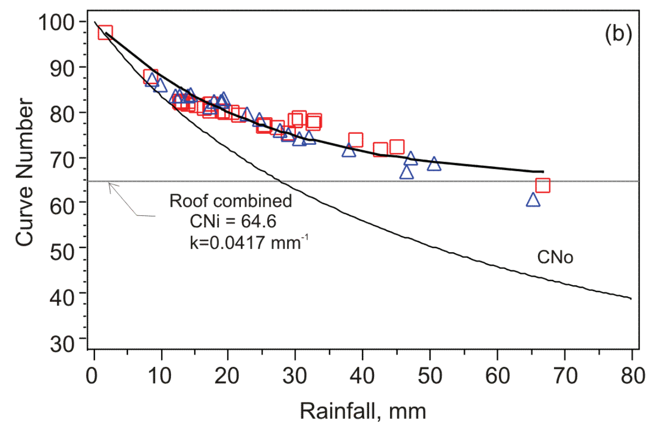


Figure 4. Comparison of asymptotic curve fittings for WS185 (roof-d) and WS192 (roof-c) for (a) full model with separate data and (b) combined model with all data.

Discussion of Curve Number Results

The results suggest that there is no difference in CN values at the small percentage imperviousness and level of connectedness in the two watersheds; the roofs showed that CN was not practically different from the meadow practice that each roof period followed. At the small percentage imperviousness investigated, connectedness is not important, even with a large structure discharging roof runoff 12 m to a swale near the mouth of a watershed. These results suggest that implementing the LID/GI principle of controlling roof runoff is not effective at the level investigated; the threshold at which many roof disconnections might have an impact was not reached.

While some results suggest a statistically significant difference in CN, the asymptotic fitting and the sum-of-squares-reduction test appears sensitive to the distribution of CN-P data being fitted, even when graphs appear to be visually similar. Data clustered where the fitted asymptotic curve is changing slope rapidly, combined with fewer large

Table 4. Comparison between roof treatments in WS185 and WS192 (units for k are mm^{-1}).

Watershed	Parameter	Final Parameter	P_{min} (mm)	Fitted Parameter Estimate	Standard Error	95% Confidence Limits Lower	95% Confidence Limits Upper	Significant Difference?
WS185 (roof-d)	CN_i	69.7	36	10.1	3.1	3.8	16.3	yes
	k	0.0557		0.0219	0.0077	0.0064	0.0375	yes
WS192 (roof-c)	CN	59.6	59	59.6	2.7	54.3	64.9	yes
	k	0.0337		0.0337	0.0039	0.0258	0.0417	yes
Combined WS185 and WS192	CN_i	64.6	48					na[a]
	k	0.0417						na

[a] na = not applicable.

Table 5. Curve-number summary within and across watersheds.

Watershed	Management Practice	Original CN_i	Original P_{min} (mm)	Combined[a] CN_i	Combined P_{min} (mm)
WS185	Roof-d	69.7	36	71.0/71.3	31
	Meadow	71.5	30		
WS192	Roof-c	59.6	59	63.2	49
	Meadow	65.4	43		
	Pasture	77.0	26	-	-
Combined WS185 and WS192	Roof-d and Roof-c	-	-	64.6	48

[a] Combined CN_i when there were no statistical or practical differences in CN_i for within-watershed comparisons.

P data, can result in nonrepresentative fitting using equation 5. When comparing CN vs. *P* curves, an analyst must use judgment regarding the effects of the distribution of CN data with *P*, as well as watershed characteristics, to draw conclusions from statistical analysis.

The results from other runoff periods have implications for managing runoff and erosion in areas subject to land disturbance for development implementing LID/GI principles. At WS192, during the 29 years the watershed was in a pasture management practice (cows), CN was noticeably larger (77.0) than the following 3.7-year period of meadow, during which CN was 64.6 on the same watershed. This decrease of 11.6 CN units (-15%) suggests infiltration can recover over a short period of time if compaction (landscape-wide disturbance similar to trampling by cows) is eliminated. This benefit is partly attributed to lack of disturbance of the soil profile, roots, and structure and macrofauna that maintain macropore continuity, and exposure of the soil to freeze-thaw cycles that shrink and swell the soil surface. Trampling by cows of the soil surface might mimic a disturbance by limited surface traffic on protected grassed areas during urbanization. CN can be expected to rapidly recover to predisturbance conditions (e.g., to a grassed field with lower CN) if the disturbances are discontinued. Consequently, managing the landscape and soil profile during development can have significant runoff-reduction benefits at little cost, for which practitioners can receive CN credit.

While disturbing only the topsoil and planting grass will have conservation benefits in general, CN can increase and remain high if the subsoil is disturbed and heavy equipment compacts the soil, as often happens during urban development. This observation was found in the experimental watershed study of the hydrological effects of drastically disturbing the landscape by mining and reclamation in three dissimilar geological profiles (Bonta et al., 1997). In that study, the entire soil profile was removed, mixed, and reapplied, causing a CN increase from various pre-mine undisturbed levels to an average of 89 after reclaiming the landscape by revegetating with grass in the three watersheds. No recovery was apparent during a three-year post-reclamation monitoring period. The large post-reclamation CN values ranged from 87 to 91 and were nearly the same regardless of the characteristics of the geological profile from which the three sets of soils were originally derived. This post-disturbance CN convergence suggests the use of CN of ~89 for drastically disturbed area. Minimizing the disturbance to the soil profile during development is an opportunity to avoid potentially large runoff volumes when employing LID/GI recommendations.

Minimum event precipitation values for the five separate practices (WS185 and WS192) ranged from 26 to 59 mm, with an average of 38 mm and coefficient of variation of 0.35. The minimum P_{min} was found for pasture, which had the largest CN_i and *k*. This suggests that for a widespread disturbance, such as trampling by cows, CN_i is applicable for smaller storms. A summary of CN_i values found within and across watersheds, P_{min}, and subsequent combining of data is shown in table 5.

Relative Peak Flows and Causal Rainfall Intensities

Empirical frequency distributions of peak flow index show that meadow had smaller index values (average = 0.211) than roof-d (average = 0.232) at WS185 (fig. 5a). While the averages were close, visually roof-d data were larger for smaller values and appeared to be the same for larger values. The difference was not statistically significant at the 0.096 level. At WS192, meadow (average = 0.254) and roof-c (average = 0.220) were also statistically the same (fig. 5b). Visually, the larger roof-c values

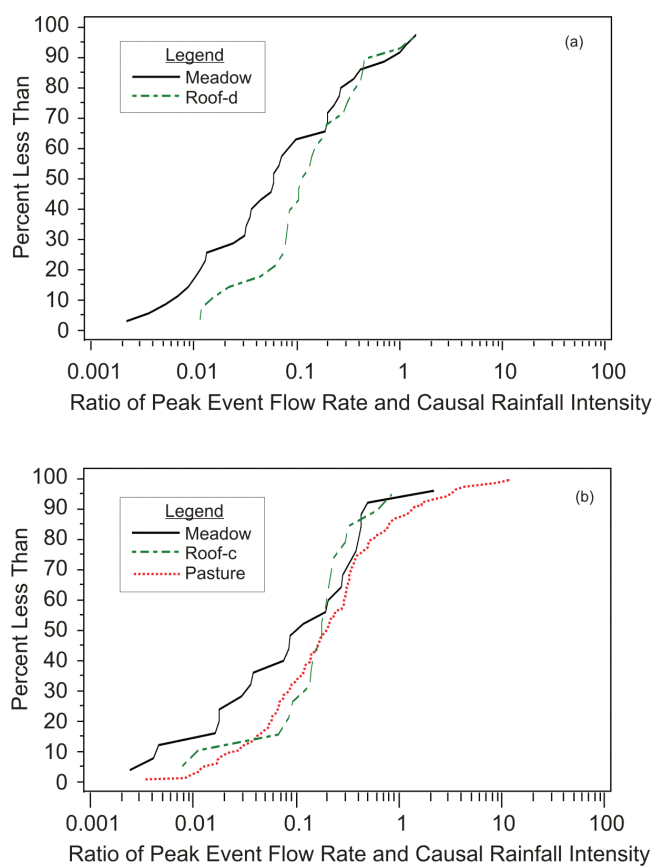


Figure 5. Empirical frequency distributions of ratios of peak runoff to causal rainfall intensities (peak-flow index) for (a) WS185 and (b) WS192.

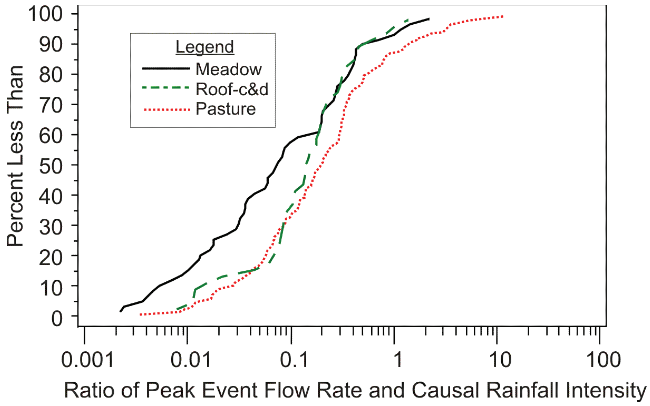


Figure 6. Empirical frequency distributions of ratio of peak runoff to causal intensities for pooled WS185 and WS192 data.

followed the same pattern found for roof-d and meadow in WS185. The pasture index (average = 0.611) is located to the right in the graph and was statistically larger than meadow at the 0.020 level but was significant at the 0.058 level when adjusted through the Bonferroni test, suggesting a borderline significance. As with CN, the pastured watershed recovered to a statistically significant lowering of peak flow response in the short 3.7 years during which the practice was meadow.

Data pooled by land management across watersheds showed that there was a statistical difference between indexes for meadow (average = 0.229) and pasture (average = 0.611) at the 0.005 level (0.016 after the Bonferroni adjustment), suggesting that peak flow response for pasture is larger for a given causal rainfall intensity (fig. 6). A statistical difference was found between meadow and roof-c and roof-d (average = 0.227) at the 0.049 level (0.148 after the Bonferroni adjustment). However, the conclusion is that there is practically no difference between roof-c and roof-d and the meadow peak-flow response. Consequently, spatial location and percentage imperviousness evaluated in the present study have no effect on peak flows.

In the mine reclamation study (Bonta et al., 1997), peak flow index did not recover during the approximately three-year post-reclamation period at two of the sites but appeared to recover at the third site. The soil profile disturbances during mining and reclamation operations suggest that peak flow response to destruction of the soil profile tends to maintain larger peak flows.

Conclusions

A study was conducted on the effects of low percentage imperviousness (~0.6%), spatial location of imperviousness, and landscape management on watershed infiltration through the curve number (CN) and on peak-flow rates. Precipitation and runoff data were analyzed from two ~3 ha experimental watersheds (WS185 and WS192) located at the North Appalachian Experimental Watershed at Coshocton, Ohio. The two-parameter (CN_i, k) ordered asymptotic method of Hawkins (1993) was used to determine CN. The sum-of-squares-reduction test was used to statistically compare the fitted curves within and among watersheds. Land management for the three sites included pasture (cows), meadow, and two roof configurations, each consisting of a 189 m^2 low gable roof structure. At one site, the roof was placed distant (disconnected) from the stream channel (identified as roof-d), and the other roof was placed close to the stream channel near the watershed outlet (connected; identified as roof-c) to investigate spatial location of imperviousness. Additionally, results from a previous study investigating the impacts of drastic land disturbances due to mining and reclamation were included to extend the investigation of soil surface disturbances to drastic soil profile disturbances. The practices studied support low-impact development (LID) and green infrastructure (GI) principles. The following conclusions can be made regarding runoff impacts due to landscape disturbances affecting the soil surface and soil profile:

CN computed from data with a roof close to the stream channel (roof-c) and distant from the channel (roof-d) were both not significantly different from the meadow practice that preceded their installation in each watershed, suggesting no effect of percentage imperviousness or spatial location of a low level of percentage imperviousness. At the small percentage imperviousness, LID/GI connectedness is not important, even with a large impervious structure discharging roof runoff within 12 m of a swale near the mouth of a small watershed.

Properly managing the landscape soil surface during development, as suggested by LID/GI concepts, can have significant runoff-reduction benefits at little cost. The data suggest that it is likely that infiltration will recover (smaller CN) if surface traffic is eliminated and soil profiles are not disturbed. CN decreased 11.6 CN units (-15%) during a 3.7-year meadow management (CN = 65.4) after a 29-year period of trampling by cows (CN = 77.0).

An index of peak flow impacts due to roof placement and meadow (peak runoff rate/unit of causal rainfall intensity) was statistically the same for meadow and either roof-c or roof-d, suggesting no impact of spatial location or percentage imperviousness on peak flow response to rainfall.

While there was no effect of roofs on peak flows, meadow management (discontinuation of soil surface disturbances due to grazing) resulted in a significant lowering of peak flows.

CN can increase and remain high if the soil profile is disturbed and compacted by heavy equipment, as observed in an experimental watershed study of the hydrological effects of drastically disturbing the landscape by mining and reclamation. In that study, experimental watersheds with dissimilar geologic and soil characteristics before each watershed was disturbed (natural conditions) were mined by removing and reapplying the entire soil profile during and after extraction of coal, causing CN to increase at each site to approximately 89, even after reclaiming the landscape by revegetating with grass. No recovery of CN was apparent during a three-year post-reclamation monitoring period. Peak flow index also remained higher after reclamation, but tended to recover at one of the three sites. From a CN standpoint, disturbances that disrupt the soil profile should be avoided.

The sum-of-squares-reduction test works well to identify differences in CN and k due to watershed treatments, but the results can be sensitive to the distribution and clustering of CN-P values. Interpretation of statistical results must consider the distribution of data entering a regression fit as well as watershed characteristics when drawing statistical conclusions regarding watershed treatment comparisons.

Analyzing and synthesizing existing experimental watershed data has the potential to provide relatively rapid guidance on infiltration and runoff control because data are often readily available with a wide range of weather experience and under controlled conditions.

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